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Pelletron-based MeV-range electron beam recirculation

A.C. Crawford, S. Nagaitsev*, A. Sharapa[1], A. Shemyakin[1]

Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA

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Abstract

In this paper we describe the successful recirculation of a DC electron beam at energies 1–1.5 MeV and currents up to 0.7 A with typical relative losses of $5\text{–}20 \times 10^{-6}$. Currents of 200 mA were maintained for periods of up to five hours without a single breakdown. We found that the aperture-limiting diaphragm in the gun anode significantly increased the stability of the recirculation. We also found that the stability depended strongly on vacuum pressure in the beamline. The performance of the collector with transverse magnetic fields was found to be adequate for beam currents up to 0.6 A, which is in agreement with our low-energy bench test results. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Although electron cooling [1] has become a routine tool in many laboratories, its use has been restricted to low-energy accelerators (< 500 MeV/nucleon). In 1995 Fermilab has undertaken an R&D program in electron cooling that has two principal goals: (1) to determine the feasibility of electron cooling the 8.9 GeV/c momentum antiprotons; and (2) to develop and demonstrate the necessary technology. The primary technical problem is to generate a high-quality, monochromatic, DC, multi-MeV electron beam of 200 mA or greater. The technical goal set for a proof-of-principal demonstration using mostly existing equipment was to maintain a 200 mA beam for the period of one hour. The only technically feasible way to attain such high electron currents is through beam recirculation (energy recovery). Although the recirculation tests [2], described in this paper, used a 1–1.5 MeV electron beam and the Fermilab electron cooling system requires a 4.3 MeV beam, the demonstration is relevant because the increased energy does not involve fundamental changes in technology.

2. Setup description

This demonstration was performed using a 2 MeV Pelletron™ accelerator (Van de Graaff type) at National Electrostatics Corporation (NEC), Middleton, Wisconsin. It is the same accelerator as described in Refs. [3,4] with shorter acceleration

* Corresponding author. Tel.: 1-630-840-4397; fax: 1-630-840-8737.

[1] Permanent address: Institute of Nuclear Physics, 630090, Novosibirsk, Russian Federation.

E-mail address: nsergei@fnal.gov (S. Nagaitsev)

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and deceleration tubes, a new electron gun and collector [5], as well as a different beam line. Fig. 1 shows the test beamline layout. Table 1 summarizes the important system parameters. This system employs the Pelletron accelerator with a maximum charging current of a few hundred microamps (typically 50–100 μA). The electron beam line consists of a 7.5 m long channel with discrete focusing elements (lenses and a 180° bending magnet) flanked by small aperture (2.54 cm ID) acceleration and deceleration tubes.

Fig. 2 shows the simplified electrical schematic of the electron recirculation system. The loss current was measured as a load on the anode power supply (see Fig. 2). Current load on this supply is nearly always equal to or slightly greater than the total current loss measured by a Pelletron voltage regulation circuit. This is because some of the electrons originating from the cathode can be lost to the gun (or collector) anode without contributing to the Pelletron losses. However, the anode supply current was measured with greater precision and, unless noted otherwise, we will use it to describe the current losses.

Table 1
Recirculation system parameters

Parameter	Symbol	Value	Units
Pelletron voltage	U_0	1–1.5	MV
Max. recirculated			
Beam current	I_b	0.7	A
Typical vacuum	p	$0.2\text{–}1 \times 10^{-7}$	Torr
Relative losses	$\Delta I/I_b$	$0.5\text{–}2 \times 10^{-5}$	
Electron gun			
Cathode radius	R_c	1.7	mm
Gun perveance	P	0.02–0.08	μPerv
Anode voltage	U_A	$\leqslant 50$	kV
Control voltage	U_C		
Beam off		$-U_A/13$	
Beam on		$-U_A/100$	
Electron collector			
Collector voltage	U_{COL}	$\leqslant 5$	kV
Relative losses		3×10^{-6}	
(30 keV bench test)			

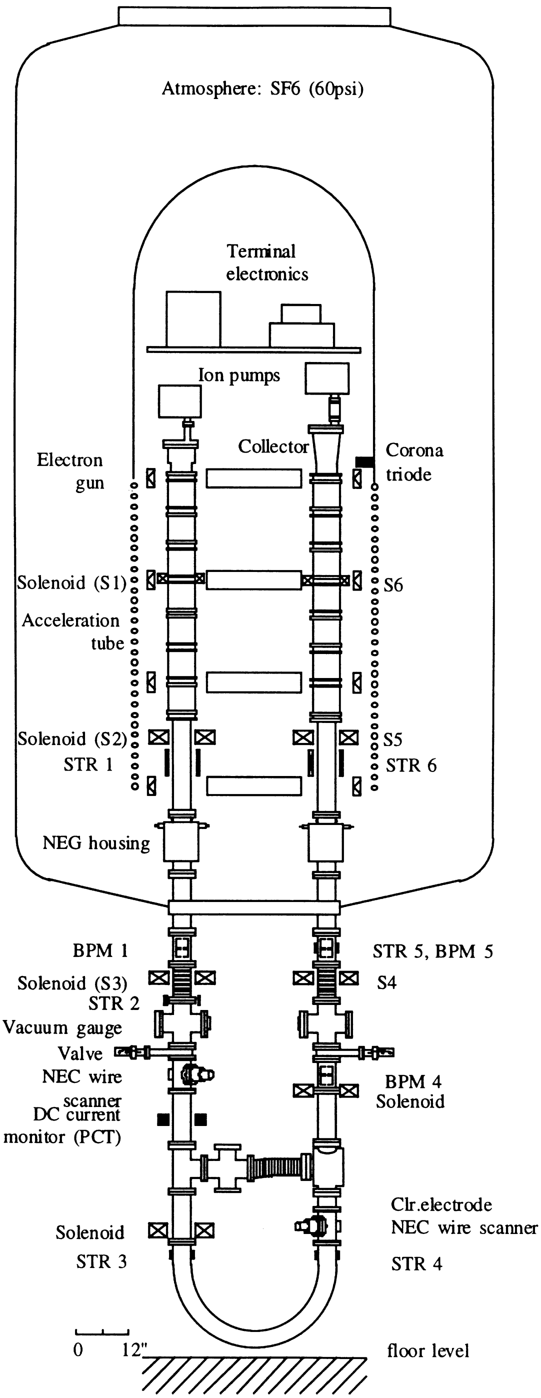

Fig. 1. Recirculation system beamline layout.

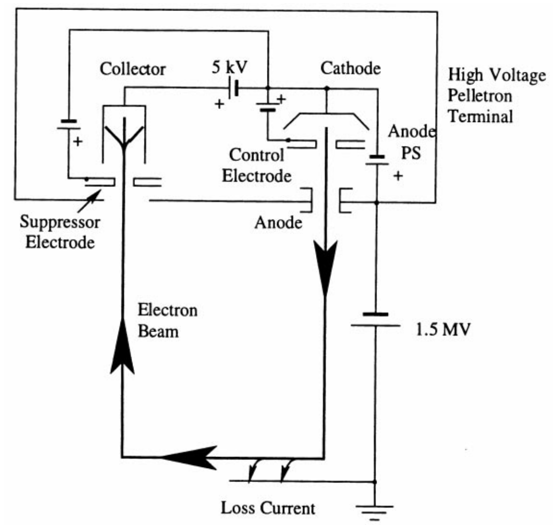

Fig. 2. Simplified electrical schematic of the electron recirculation system.

3. Stability

For a relatively simple beamline such as in Fig. 1 the computer modeling allows to simulate the beam envelope and to determine the beamline settings that would keep the beam size small for all beam currents up to several amps. Nevertheless, initially we were unable to recirculate beam currents of more than a fraction of a milliampere. In the attempt to further increase the beam intensity the Pelletron voltage would usually drop ("crash") instantly to a very low level. To reset the system back into the recirculation state one has to close the gun, allow the Pelletron voltage to stabilize at a megavolt level, and then open the gun. These crashes were of primary concern in our test.

The first and the most obvious reason for a crash is an overvoltage on the acceleration and deceleration tubes. The frequency of such non-beam-related crashes depends significantly on a Pelletron voltage and a particular state of the tubes, vacuum and other factors. In our tests the Pelletron voltage was lowered from a nominal 2 to 1–1.5 MV in order to both reduce the frequency of such breakdowns and to minimize the damage to the terminal electronics caused by these breakdowns.

Second, the behavior of the high-voltage regulation system in this specific Pelletron becomes unstable if the total current losses to ground are greater than 10–20 μA (depending on the Pelletron voltage). If the losses exceed this level the Pelletron voltage starts to droop, the beam is then shifted from the collector because of a non-zero dispersion function, the recirculation is lost and the Pelletron capacitance is discharged by a current that does not exceed the nominal beam current. If the gun remains open, the electron beam, lost to the acceleration tube, forms a potential barrier such that nearly all the beam is reflected back to the gun anode. The Pelletron voltage in this stable state does not typically exceed several hundred kilovolts. Note that the time of such a discharge is much longer than in the case of a high-voltage breakdown, when all the tubes are shortened by plasma. As a result, these crashes do not damage the electronics inside the high-voltage terminal. Usually, this process is important in cases of the beam scraping, or if the collector performance is inefficient.

The system behavior is similar when current losses remain small but the derivative of the current losses with respect to the beam energy is negative. For instance, suppose that as the beam energy decreases the beam is shifted inside the collector so that the trajectories come even nearer to a collector wall. In this case the current losses increase and the energy drops further due to a positive feedback mechanism. If this derivative is high enough and the high-voltage regulation system has no time to correct the fluctuation, the scenario is the same as in the previous case.

A specific place where current is lost greatly affects for the stability of operation. We had recirculated the milliampere range beam with losses to the gun anode up to hundreds of microamperes, but we have never seen a change in the tube resistive divider current of more than a couple of microamperes. Two mechanisms can explain crashes occurring before higher losses in the acceleration tubes.

(a) The tube resistive divider current is typically 25 μA at 1 MV. The loss of 1 μA redistributes potential along the tube by kilovolts. For regimes with a high beam current, a strong influence of the beam space charge on the electron trajectories can act as a positive feedback mechanism when the lowering of the potential downstream of the gun anode increases the current loss and, in turn, lowers the potential further.

(b) The lost electrons charge the tube ceramic and provoke partial discharges in the tube. Discharges in the upper part of the tube can increase the current loss as in (a). Also, the probability of a full tube breakdown increases with the frequency of the partial discharges.

It is difficult to measure precisely the current losses to the tubes in this setup and describe quantitatively stability as a function of the losses. We can only note that the current to the tubes of approximately a microampere corresponds to the operation time without a crash of not more than several minutes. Usually, we use a radiation monitor placed opposite the acceleration tube to judge the level of the losses. As a rule, a nonlinear increase of this radiation with the beam current indicates poor stability.

Thus, to have stable beam recirculation, it is necessary to have low total current losses and very low losses to tubes.

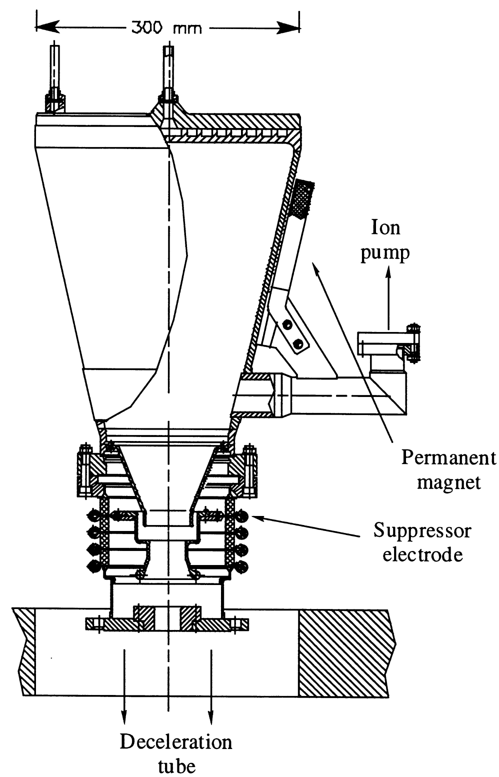

Fig. 3. Mechanical schematic of the collector.

4. Collector performance

Initially, the main reason for the crashes was high current losses from the collector. The collector used in these experiments is shown in Fig. 3. An initial version of the collector was axially symmetric (without a permanent magnet), and the secondary electrons were captured by the collector cavity because of its large surface area and a small entrance hole, and by a potential barrier near the collector entrance [6]. This barrier is created by a special electrode a.k.a. a suppressor. A typical feature of such a collector is a linear dependence of the current losses on the suppressor potential (symbol ○ in Fig. 4). The maximum recirculated current was 20 mA with the relative current losses of about 10^{-4}.

The losses decreased by an order of magnitude when a system of permanent magnets was attached to the collector (see Fig. 3). These magnets form a transverse magnetic field to prevent the secondary electrons from leaving the collector cup [5]. In

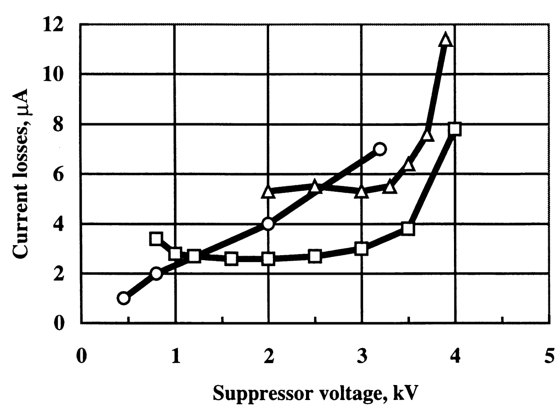

Fig. 4. Measured current losses as a function of the suppressor electrode voltage ($U_{COL} = 4$ kV) for the collector without the magnetic field (symbol ○, beam current is 12 mA) and for the collector with the transverse magnetic field: beam current is 150 mA (□) and 300 mA (△). $U_0 = 1.135$ MV and $P = 1.0 \times 10^{-7}$ Torr.

this case, there is a plateau in the current losses as a function of the suppressor voltage (Fig. 4).

Fig. 5 shows the current losses as a function of the transverse beam position at the collector entrance for various beam currents. The beam is displaced by a steerer upstream of the deceleration tube (STR 6, Fig. 1). At low beam currents (< 10 mA) a maximum displacement is defined by the primary beam scraping. We can use this fact to convert steerer current into the actual displacement measure. Simulations show that the beam size near the collector at low current is several millimeters which is much less than the physical aperture limit (28 mm). In such a regime, the steerer current can be varied by as much as 0.22 A without an increase in current losses. We can conclude from Fig. 5 that the beam with current up to 200 mA can be displaced inside the collector by a centimeter with good collector efficiency. At currents above 600 mA such a freedom in the beam position disappears and the current losses start to increase nonlinearly. This result is in agreement with measurements at a low-energy test bench [5].

Probably, the secondary electron flux from the present collector does not play a major role in the system operation at beam current less than 600 mA.

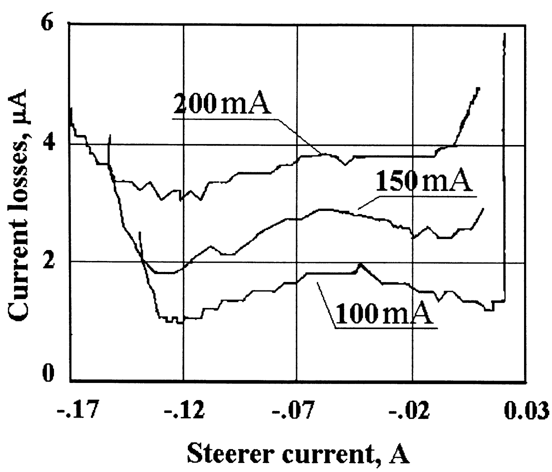

Fig. 5. Current losses as a function of the transverse beam position in the collector for various beam currents. The Pelletron voltage was $U_0 = 1.135$ MV, anode voltage 31 kV, collector voltage 3.2 kV, and collector suppressor voltage 2.2 kV.

5. Electron gun performance

While the collector is efficient and the primary beam is transported without scraping, the system stability strongly depends on the beam current. One can consider the maximum recorded recirculation time without a crash as a characteristic of the operation stability. This time drops dramatically with the beam current and depends on a gun configuration. We can only explain this behavior by a beam halo generated in the gun.

Fig. 6 shows the mechanical schematic of the electron gun. The beam current is controlled by a special electrode near the cathode (control electrode). The control electrode is negatively biased with respect to the cathode to suppress the emission from the cathode's side surface [5]. The gun is closed if the control electrode voltage is equal to $-\frac{1}{13}$ of the anode voltage. Another feature of this gun is a permanent magnet ring installed inside of the anode (Fig. 6). This magnet provides the beam focusing needed to compensate for the anode–hole defocusing effect.

We tested the electron gun both without a diaphragm and with one diaphragm, placed in either of two positions as shown in Fig. 6. All three of these gun geometries have the same perveance and produce an electron beam of identical properties. Moreover, current losses for these three gun geometries are equal (at least up to 200 mA beam currents) for a given pressure and beam line

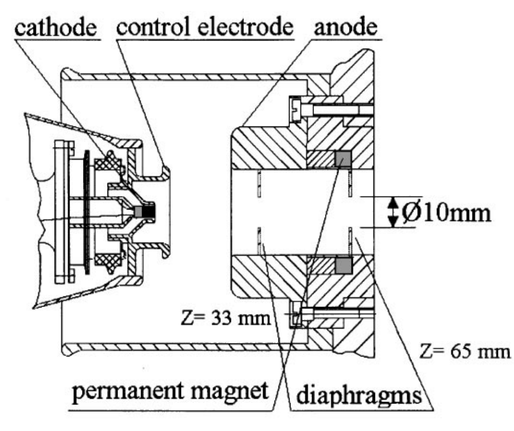

Fig. 6. Mechanical schematic of the electron gun. Cathode diameter is 3.4 mm.

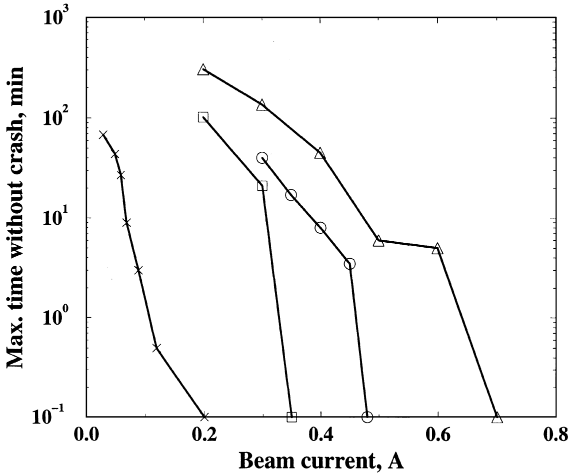

Fig. 7. Maximum recirculation time without a crash as a function of the beam current. Results are shown for three gun designs. The only difference between the guns is an anode diaphragm position: (×) – no diaphragm installed, (□) – diaphragm at $Z = 65$ mm, (○) – diaphragm at $Z = 33$ mm (pressure $p = 1 \times 10^{-7}$ Torr for all three curves), and (△) – $Z = 33$ mm; $p = 2 \times 10^{-8}$ Torr. Beam energy is about 1.2 MeV.

settings. Nevertheless, one can see from Fig. 7 that the installation of a diaphragm as well as the vacuum improvement both contribute to the increased recirculation stability. We propose the following mechanism to qualitatively explain this behavior of the recirculation system.

Primary electrons ionize the residual gas atoms. The ions are accelerated to the gun and knock secondary electrons from both the cathode surface and the control electrode surface. If these secondary electrons reach the acceleration tube walls, they charge the ceramic and initiate partial tube breakdowns. Secondary particles produced in these partial breakdowns, in turn, initiate a crash possibly through an avalanche mechanism.

The same process exists in the deceleration tube as well. However, the secondary electrons emitted from the collector surface never leave the collector. In a sense, the gun needs to be made similar to the collector so that the secondary electrons are captured inside the gun.

The most obvious possible emitter of such secondary electrons is the cathode. The gun employs a dispenser cathode that has an intentionally low work function. Probably, the coefficient of the secondary electron emission by an ion impact can be significantly higher for the hot cathode surface than a typical value of this coefficient for most of metals, which is 1–4 in the MeV ion energy range [7]. On the other hand, the majority of these secondary electrons has energy below 10 eV [7] and their trajectories are close to the ones of the thermally emitted electrons. Results of gun simulations with Super SAM code [8] show that the secondary electrons emitted from the cathode with transverse energy up to 50 eV in the presence of the primary beam are not captured by the diaphragm and can be transported through the acceleration tube.

The backstreaming ions can also hit the control electrode. The electrons emitted from the control electrode experience large transverse electric fields in the gun and have trajectories terminating on the acceleration tube electrodes. Fig. 8 shows the example of a gun simulation with the secondary electrons being emitted from the control electrode. These electrons are most likely responsible for the majority of the beam-related crashes. A diaphragm installed in the gun anode scrapes most of these electrons, thus, increasing the recirculation stability.

Similarly, the vacuum improvement reduces the number of the residual ions and, consequently, the number of secondary electrons capable of reaching the acceleration tube walls. Experimental results with the improved vacuum are also shown in Fig. 7.

There are two obvious dangers associated with a diaphragm installed in the gun anode:

- The first is the secondary electron emission from the diaphragm itself. To suppress this emission the diaphragm was installed in an almost equipotential space inside of the gun anode. Simulations show that all of the secondary electrons, originating from the diaphragm, travel along the magnetic field lines of the permanent magnet ring (Fig. 6), and are absorbed on the anode surface.
- The second is the scraping of the primary beam. Fig. 9 shows the current losses for two different positions of the diaphragm. If the diaphragm is installed at $Z = 65$ mm position, the maximum beam current is limited by a nonlinear increase of

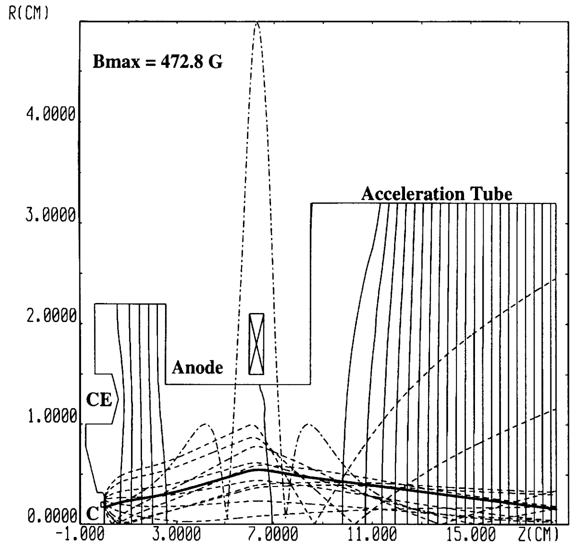

Fig. 8. Electron gun simulation. Thick solid line is the primary beam envelope, thin solid lines are the equipotentials spaced every 5 kV, dash-dotted line is the absolute value of the magnetic field along the axis, and dashed lines are the secondary electron trajectories. Secondary electrons are emitted from the control electrode (item CE) with initial energy of 1 eV. Anode potential with respect to the cathode (item C) is 30 kV, control electrode voltage is -0.31 kV, and beam current is 250 mA.

the current losses. In such a case, the anode power supply current shown in Fig. 9 is typically an order of magnitude higher than the current losses to ground.

One can calculate a maximum gun perveance by the maximum current achieved for a given anode voltage. The perveance is determined by the beam geometry. The beam scraping corresponds to a specific beam size in the anode approximately equal to the diaphragm diameter. As a result, the maximum gun perveance does not depend on the anode voltage as is the case in Fig. 10, Curve 2.

The maximum current limitation is different for the diaphragm at $Z = 33$ mm. The current losses are approximately linear with beam current up until the final crash occurs. The maximum perveance does not depend on the pressure, and is close to the perveance of the gun without the diaphragm at low anode voltages (Fig. 10, Curves 1, 3, and 4). The maximum perveance value is reproduc-

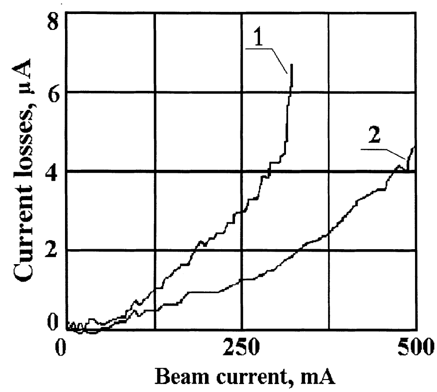

Fig. 9. Measured current losses as a function of the electron beam current. Curve (1) $- p = 1.0 \times 10^{-7}$ Torr, the anode diaphragm is at $Z = 65$ mm. Curve (2) $- p = 1.7 \times 10^{-8}$ Torr, the diaphragm is at $Z = 33$ mm. $U_0 = 1.135$ MV, $U_A = 39$ kV and $U_{COL} = 4$ kV for both curves.

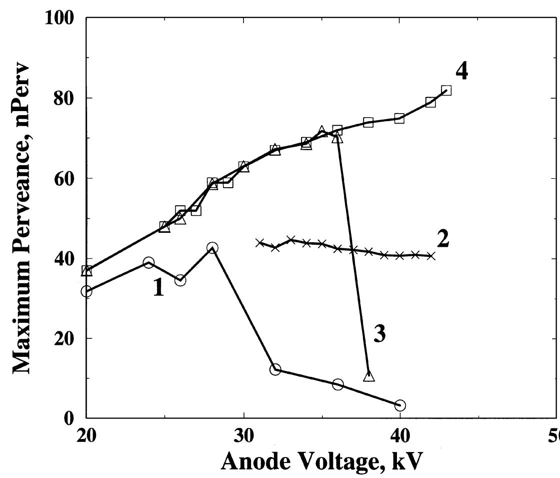

Fig. 10. Maximum gun perveance as a function of the anode voltage: Curve 1 — no diaphragm installed, Curve 2 — diaphragm is at $Z = 65$ mm position, Curve 3 — diaphragm is at $Z = 33$ mm (pressure $p = 1 \times 10^{-7}$ Torr for all three curves), and Curve 4 — $Z = 33$ mm; $p = 2 \times 10^{-8}$ Torr.

ible with precision better than 10 percent in various runs, while the time without a crash at a given current can differ by a factor of two. Beam simulations of the entire acceleration tube show that Curve 4 might correspond to a beam size being close to the tube aperture limit at the location of the first focusing solenoid (solenoid S1 in Fig. 1) or at the tube exit.

Note that generally the stability of operation improves with the decreasing of the anode voltage. The time without crashes is the longest for a given current when the chosen anode voltage provides the maximum current 10–20% above the current under measurement. Most of the data in Fig. 7 was obtained in such conditions.

6. Current losses

The current losses increase nearly proportionally with the beam current if the latter is far from its maximum value (Fig. 9). The proportionality coefficient changes linearly with the residual gas pressure in the system (compare two curves in Fig. 9). The same dependence was observed in tests of the gun and collector at a low-energy test bench [5]. The coefficient was in agreement with the residual gas ionization model. Similar estimation was done for the Pelletron test by the integration of the ionization cross section as a function of the electron energy along the beam trajectory. For this estimate we used a formula from Ref. [9] for the ionization cross section of H_2. The coefficient of 8 Torr^{-1} was found (i.e. the relative current losses due to the process are 8×10^{-7} for the system pressure of 1×10^{-7} Torr). This value is more than an order of magnitude lower than the experimentally observed one. Most probably, the main contribution to the current losses comes from the secondary electrons originating from the cathode surface since the coefficient of the ion/electron emission from the cathode is likely to be very high. We have only indirect confirmations of such a mechanism. One of them is the fact that the losses depend on a pressure in the beamline at ground, but do not depend on the vacuum near the gun or collector.

7. Effects of total beam energy

Most of the studies and system modifications were done at two Pelletron voltage levels: 1.13 and 1.50 MV. We found the same current losses and similar maximum attainable beam currents for both levels. The detailed study of the recirculation stability was done for the beam energy of 1.16 MeV only because of inadequate radiation shielding in the Pelletron control room. At 1.53 MeV we recirculated current of 500 mA for a short time period, and 200 mA for up to 50 min without crashes. It is difficult to determine the main reason for the difference in the results for two beam energies. An increased electric field strength in the tube can be one of the reasons. Another reason could be that we spent significantly less time studying the system at the higher of these two energies. On the other hand, the main progress in the system performance was achieved due to the modifications at the low-energy end of the device: in the gun and in the collector. This gives us hope that the performance will not worsen significantly for a Pelletron with higher energy and longer tubes.

8. Conclusions

1. An electron beam with current of hundreds of milliamperes and energy of 1–1.5 MeV was recirculated in a DC regime. At energy of 1.2 MeV typical time between crashes is several hours for the beam currents of 0.2 A; the maximum recirculated current is 0.7 A. The goal of the test (0.2 A during one hour) has been achieved.
2. The time of operation without crashes is determined by discharges originated in the acceleration tube. The discharges are probably triggered by the secondary electrons knocked from the control electrode by the residual gas ions.
3. A diaphragm inside the anode confines the secondary electrons and significantly improves the system performance.
4. Both current losses and the operation stability depend on the pressure (in the range of 10^{-7}–10^{-8} Torr).
5. Relative current losses from the collector do not exceed 5×10^{-6} for the beam current of up to 0.5 A.
6. The Pelletron-based recirculation scheme seems to be applicable for the multi-MeV range of the beam energy since all of the limitations are originating from the low energy part of the system.

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